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Clementine Dosimetry

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This paper presents radiation dosimetry results from the Radiation and Reliability Assurance Experiments on the Clementine spacecraft and Interstage Adapter Satellite. The dosimetry instruments utilize low dose response p-channel Field Effect Transistor and proton sensitive Static Random Access Memory dosimeters. These dosimeters successfully demonstrated an order of magnitude decrease in instrument weight and power over previous systems. The data confirms pre-launch predictions of the total dose effects on Charged Coupled Device dark current and on Complementary Metal Oxide Semiconductor 1.2 and 0.8 μm technology design and process parameters in the space environment. A solar proton event during the early phases of the mission allowed a comparison between the Clementine measured proton fluence and energy spectra and the Geostationary Operational Environmental Satellite number 6 measured proton fluence and energy spectra, These data confirmed the proton spectrometer design and operation.

NOMENCLATURE

Variable	Description
all	second order polynomial coefficients
C^{u}	upset capacitance
D_S	space measured radiation dose
D(T)	temperature corrected space radiation dose
ΔE	SRAM proton energy window width
E_g	silicon band gap energy
f_e	proton internal environment fraction
f_{on}	SRAM on time fraction
F(E)	external proton fluence
G	pFET temperature independent circuit gain
If)	CMOS drain current
I_d	CCD dark current damage factor (nA/cm^2- krad)
I_g	prelaunch CCD2 dark current
k	Boltzmann's constant
K	charged particle produced ionization per unit energy 10ss in silicon (fC/MeV)
Kp	planetary magnetic index
N	SRAM measured number of counts per hour
N_T	number of pixels per SRAM chip
T_S	space measured z-DUT board temperature
V_C	CCD2 current to voltage conversion factor
V_d	pFET temperature independent threshold voltage damage factor (mV/krad)
V_{DD}	SRAM chip bias voltage
V_g	ground measured voltage
VG	CMOS gate voltage
V_O	SRAM adjustable offset voltage
AV_p	SRAM offset voltage above rnem-stable point
V_S	space measured voltage
VT	CMOS threshold voltage
VT_d	CMOS threshold voltage damage factor (mV/krad)
VT_S	CMOS space measured threshold voltage
VT_t	CMOS threshold voltage temperature factor (mV/°C)
V_0	CCD2 extended pixel voltage mean
σ	SRAM pixel sensitive area or "cross section"
Ω	Clementine SRAM field of view

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1NTRODUCTION

The mission goal of the Clementine Engineering Experiments Program was to evaluate the effects of the space environment on advanced Ballistic Missile Defense Organization (BMDO) technologies being flight tested on the main Clementine spacecraft and the Interstage Adapter Satellite (ISAS). The Radiation and Reliability Assurance eXperiment (R{RELAX) instrument contributed to the flight qualification of advanced BMDO technologies by preforming radiation dosimetry in the space environment. The RRELAX dosimetry instruments utilized Jet Propulsion Laboratory (JPL) low dose response p-channel Field E. ffect Transistor (pFET) and proton sensitive Static Random Access Memory (SRAM) Integrated Circuit chip (IC-chip) dosimeters. These dosimeters, collectively called RADiation MONitors (RADMONs), demonstrated an order of magnitude decrease in instrument weight and power over previous systems.

Dosimetry data for the Clementine spacecraft, On 21 Feb. 1994 and 12 May 1995, and IS AS, throughout its mission, are presented in this paper. The ISAS pFET data confirmed pre-launch predictions of the total dose effects on Charged Coupled Device (CCD) dark current and on 1 Iewlett-Packard (HP) 1.2 and 0.8 μm technology design and process parameters in [he space environment. A solar proton event during the early phases of the mission allowed a comparison between the Clementine RRELAX measured proton fluence and energy spectra and the Geostationary Operational Environmental Satellite number 6 (GOES-6) measured proton fluence and energy spectra. These data confirmed the SRAM proton spectrometer design and operation.

RRELAX EXPERIMENT DESIGN

Two identical RRELAX experiments flew on the Clementine missions-one on the Clementine spacecraft and one cm the IS AS. The RRELAX experiments arc autonomous micro processor controlled data handling and analog test systems. They were contained on three Device Under Test (DUT) boards. These boards, termed the x, y, and z-DUT boards, are shown in Figure 1. The z-DUT board, which contains most of the RRELAX experiments, is mounted on the top of the RRELAX box normal to the 7.-axis.

The data presented in this paper were generated by the z-DUT board RADMONS and CCD2. Each DUT board was covered with a 0.5 roil, Al equivalent, aluminized kapton dust cover while RADMON(Z2), which had no Kovar lid, was covered with an additional 0.5 mil aluminized kapton dust cover. CCD2 had a 15 mil Kovar lid, RADMON(Z3) a 10 mil Kovar lid, RADMON(Z5) two 10 mil Kovar lids, and RADMON(Z4) three 10 mil Kovar lids. The ISAS RRELAX was also covered by a 6 mil Al equivalent thermal blanket.

The z-DUT board RADMONs were fabricated through MOSIS at HP Corvallis in 1.2 pm technology and the JPL CCD2s at Loral. A pFET dosimeter and SRAM proton counter was contained on each 1.2 μm RADMON IC-chip (Z2, Z3, 25, & Z4) on the z-DUT board, shown in Figure 1.

pFET DOSIMETER SYSTEM DESIGN

The pFET dosimeter system was designed to measure total dose from all radiation types. The sensors were placed behind four different shielding thicknesses to produce dose-depth curves for the Clementine and ISAS experiments.

The dosimeter consisted of a pFET that was operated in a constant current mode (Figure 2). This allowed the temperature effects on channel mobility and threshold voltage to cancel each other. The objective of this design was to minimize temperature effects and emphasize dose dependence. The pFETs have a closed geometry gate eliminating the source to drain "bird's beak" leakage path. Dosimetry measured via the pFET threshold voltage shifts was influenced by two second order effects: (a) the temperature sensitivity of the transconductance factor and the threshold voltage, VT, and (b) the source to drain "bird's beak" leakage current. The goal in developing the advanced pFET dosimeter was to minimize or eliminate these effects[1].

The pFET dosimeters were only powered during readout and accumulated dose while in an unpowered state. The four pFET dosimeters were read once per hour and their data from the previous hour overwritten. Because pFETs are integrating dosimeters and have a larger radiation damage factor when unpowered, this mode of operation is satisfactory.

SRAM PROTON SPECTROMETER SYSTEM DESIGN

The SRAM proton spectrometer system was designed to measure the proton energy spectrum and fluence for use in computing proton fluence and energy at the Clementine experiments, Four shielding thicknesses were used to pick-off the external proton environment at four different energies allowing the energy spectrum to be measured. Two energy bins were used to allow heavy ion and proton-induced nuclear reactions to be subtracted from the proton data. The threshold of the proton-sensitive bin was set just below the proton Bragg peak to optimize the energy measurement.

The SRAM detector' design was fabricated in 1.2-μm, n-well, double-metal CMOS/epi. A schematic diagram of the SRAM cell, or pixel, is shown in Figure 3. This cell differs from that of a standard six-transistor SRAM cell in three ways: (1) the source of the pFET, Mp2, is connected to an adjustable offset voltage, V_0, instead of V_{DD} to provide a control of the cells upset capacitance; (2) the drain area Dn2 of nFET Mn2 has been enlarged by a factor of four over minimum to enhance upset rates, thus reducing measurement time; and (3) the cell is imbalanced by widening Mn2 over minimum to enhance its SEU sensitivity versus V_0.

In operation, all the memory cells were written into a "sensitive" state, where Mn2 was turned OFF and Mp2 was turned ON, connecting V_0 to the bloated drain, Dn2. V_{DD} was then lowered to 3 V and V. was lowered below V_{DD} = 3 V allowing the SRAM to accumulate upsets at a given V. value. Thereafter V_0 and V_{DD} were returned to 5 V and the cells read m determine the number of upsets[2].

Four SRAM chips were mounted to face along the z-axis of the experiment, two facing the x-axis, and two facing the y-axis, for a total of 8 chips, as shown in Figure 1. The SRAM portion of each chip was controlled using a single V_{DD} and V. for all 8 chips. All z-axis SRAMs, and one SRAM on the x -axis and one on the y-axis, were, fabricated in 1.2 μm technology. One SRAM on the x-axis and one SRAM on the y-axis were fabricated in 0.8pm technology.

The SRAMS were made sensitive to upset by applying 3 volt-s V_{DD} and V. voltages that have the following AV_p values above the spontaneous flip voltage:

$$\Delta V_p = 0.150 \text{ V}$$
$$\Delta V_p = 1.0 \text{ V}$$

The spontaneous flip voltage is the value of V. where [he SRAM cell becomes meta-stable and spontaneously flips. The offset voltage was set above the spontaneous flip voltage by an amount AV_p to sensitize the SRAM cell to protons, heavy ions, and nuclear reactions (AV_p = 0.150 V) or to heavy ions and nuclear reactions only (AV_p = 1.0 V). The integration period for these sensitive states was a constant of 100 seconds. At the end of each integration period, each of the 8 SRAMS were evaluated for bit changes, or upsets, and the total number for each chip stored in the data structure. The data structure and software flow are shown in Figure 4.

When the evaluation of SRAM response was complete, software accumulated the upset totals. Each chip had its own accumulation, or running total, for each value of AV_p. SRAM contents were then restored to their stinting state and the second value of AV_p set for the next integration time. The experiment software alternated between the two AV_p values on a 1:1 ratio. This was done by the "SWI'I'Cl IVOLTAGE" box in Figure 4.

The 100 s integration records together with their time stamp were called the high resolution SRAM data record. Software maintained each record for one hour before disposing of it, This generated 18 consecutive sets (18 periods per hour) of 16 word records (1 for each SRAM and AV_p value) that were stored in memory. These records formed the highest resolution data set per SRAM and pcr AV_p value.

A high resolution SRAM record that was about to be discarded was accumulated into a medium resolution record, The medium resolution record accumulated or summed the 18 high resolution records for each SRAM and AV $_p$ value. Each completed medium resolution record holds integration results for a one hour period for each SRAM and AV_p value. The medium resolution records time entry represented the time when the record was formed. The software retained medium resolution records for 36 hours for a total of 576 medium resolution records. This group of records formed one medium resolution data set per SRAM and per AV_p value.

Each SRAM, for each AV_p value, measured the total fluence over the whole mission. This process used memory locations that were only added to and never overwritten. The data set was called the low resolution data set.

The SRAMs were calibrated during each medium resolution data set by measuring (he number of stuck 0s and 1s. The temperature of the analog board and the x, y, and z DUT boards and a temperature circuit calibration measurement were then stored, overwriting the previous calibration data record.

GROUND TEST D ATA

pFET dosimeters from the flight fabrication run were calibrated with the JPL CO-60 source. The CO-60 irradiation was done at room temperature to a total dose of 100 (krad(Si)). The pFETs were tested at dose levels of 20, 40, 60, 80, and 100 (krads) and at -30, 20, and 50 (°C) at each dose level. The pFETs were measured using an hp4062 parametric test system in an oven that was also cooled with liquid nitrogen so that total dose effects could be measured as a function of temperature. A temperature independent threshold voltage damage factor, V_d, of 3.68 (mV/krad) was measured. The pFET was operated in the saturation region. which was insured by connecting the gate to the drain as shown in Figure 2, and at the temperature independent point[1].

A JPL CCD from the flight fabrication run was ground tested to 4.8 (krads(Si)) in the JPL CO-60 source at room temperature and annealed at 25 (°C) for 72 hours. The CCD was characterized in the JPL CCD laboratory and a dark current damage factor, I_d, of 7.38 (nA/cm^2-krad) at 25 (°C) was measured[3].

An SRAM from the flight fabrication run was calibrated using the Caltech Tandem Van de Graaff proton accelerator with protons at 0.75. 1.0, and 2.0 MeV. The SRAM ground test response was analyze.d using the TRIM (Transport Reactions In Matter) computer code[4]. Calibration data are shown in Figure 5. The mode] used in the calibration assumed a 5 μm over layer or "dead" layer and a 7 μm charge collection depth or "depletion" depth. '1 'he proton calibration data points are the mean values of the delta offset voltage, AV_p, where one-half the protons hitting a cell sensitive volume, Dn2, cause the cell to flip. The proton data calibrated the 1.? μm technology SRAM at an upset capacitance, C_u/K = 2.667 (MeV/V), where K = 44.2 (fC/MeV) for charged particle produced ionization per unit energy loss in silicon. The measured energy, ΔE4 shown in Figure 5, is given by, $\Delta E4 = (C_u/K) \times (\Delta V_p)$. The 1 MeV energy window, shown in Figure 5, is the measure of the SRAM response to protons in the. space environment[2].

SPACE DATA

The ground lest measured CO-60 damage factor, Vd = 3.68 (mV/krad), was used to compute the space measured pFET total dose. The downlinked numbers were bits with one LSB = 1.22 mV from a 12-bit ADC measuring between O and 5 volts.

$$D_s(\mathrm{krad(Si)}) = -\frac{\text{“ -’ *}}{GV_d} \qquad (1)$$

Where, V_s(mV) is the. space measured pFET voltage, V_g(mV) is the ground measured voltage, and G = 32.7 is the circuit gain. The zero dose voltages, V_g(mV), and aluminium equivalent shield thickness, d(mils), for each flight RADMON on the ISAS

RRELAX at T = 25 ("C) and on the Clementine Spacecraft RRHAXatT=-2.41 ("C) are listed in table 1.

The pFET total dose flight results for the Clementine spacecraft on 12 May 1995 and the ISAS on 20 Apr. 1994 (ISAS 1994 day 11 O) is shown in Figure 6. The Clementine spacecraft total dose after 472 days in space is less than the ISAS over its mission life. On the Clementine spacecraft, the RADMON dosimeter circuit dynamic range was exceeded for pFET Z2 because G = 32.7 for that circuit and a total dose of 142.95 (krads(Si)) was extracted with the CMOS experiment circuit for that pFET. The ISAS pFET dosimeter mission dose profile is shown in Figure 7. The ISAS is in a 2.13 day lunar transfer orbit that penetrates the earths radiation belts causing the rapped increase in total dose.

The ISAS RRELAX CCD experiment was shielded by 52 roils (Al equivalent). Power law dose depth curves were tit to the pFET data as a function of shield thickness. The pFET measured dose at CCD2 was then extrapolated from these curves as shown in Figure 8.

The CCD2 sensor chips were 512 pixel line arrays manufactured at Loral in n-channel Metal Oxide System (nMOS) buried channel technology. The RRELAX CCD experiment measured the dark current generated voltage in the last 8 pixels, pixel 505 through 512, and the extended pixels with no photo sensors, 513 through 519. The data presented here had a photo sensor dark current integration time of onc second. IS AS CCD2 data showing the prelaunch pixel voltage mean, V_g, and the extended pixel voltage mean, for ground and space data, VO, are presented in Figure 9. The ISAS CCD2 had a prelaunch dark current measured on the flight CCD[3] of I_g = 1.4 (nA/cm^2) at 25 ("C) and a voltage conversion of $V_c = I_g/(V_g - V_0)$ = 11.7 (nA/cm^2-V).

The 25 ("C) dark current damage factor Id = 7.38 (nA/cm^2-krad) was used to compute the space measured total dose.

$$D_s(\mathrm{krad(Si)}) = \frac{V_c(V_s - V_g)}{I_d} \tag{2}$$

Where, V_s(V) is the space measured CCD voltage mean for pixels with photo sensors, pixels 505 through 512. The total dose at 25 (Y), D(T), in units of (krads(Si)) is given by,

$$D(T) = D_s\left(\frac{T}{T_s}\right)^{3/2} \exp\left(\frac{E_g}{2kT_s} - \frac{E_g}{2kT}\right) \tag{3}$$

Where E_g = 1.21 (cV), Ts is the z-DUT board temperat ure, D_s is the space measured dose from equation 2, and T = 25 (°C). Temperature corrected CCD dose data are shown in Figure 10. The temperature correction given by Eq.3 is due to [temperature changes in the intrinsic carrier density associated with bulk generation current[5].

The CCD2 dark current measured dose is compared to the pFET measured dose at the CCD in Figure 11. Two prominent geophysical events were observed during the mission. The first, a solar proton event on day 52 of 1994 (21 Feb 94), had a planetary magnetic index (Kp) of 7+ and was observed at a number of spacecraft (the proton observations will be discussed shortly). The increased dose rate after the second major event (a storm sudden commencement followed by a brief but intense geomagnetic storm on day 107) is probably due to trapped electron belt heating on days 106 and 107 of 1994 (16-17 Apr. 94). The increase implies mm-c, higher energy, trapped electrons along the ISAS orbit. Consistent with this interpretation, Kp = 8+ for the event, indicating a likely large increase in the trapped ring current and subsequent electron belt heating. There was, however, apparently no large solar proton event associated with the event,

Th c IS AS pFET dosimeter, operated at its temperature independent drain current, measured a total dose of 11.83 (krads) on day 109.99. The ISAS pFET Complementary Metal Oxide Semiconductor (CMOS) experiment, using the same pFET operated at the five different drain currents shown in Figure 12, measured a total dose, 1)('1') given by Eq. 6, of 11.47 (krads) on day 109.99. The space measured threshold voltage, VTs, is computed with Eq. 5 from second order polynomial coefficients generated by fitting drain current, ID, versus gate voltage, VG, flight data with Eq. 4 as shown in Figure 121.

$$\sqrt{ID} = a_0 + a_1(VG) - a_2(VG^2) \tag{4}$$

$$VT_s = \frac{a_1}{2a_2}\left(-1 + \sqrt{1 - \frac{4a_0a_2}{a_1a_1}}\right) \tag{5}$$

$$D(T) = [VT_s + VT_t(T_s - T) - VT]/VT_d \tag{6}$$

Where, VT_t = 1.24 (mV/°C), T = 25 (°C), and VT= 883.7 (mV) measured on the IS AS pFET prior to launch, and VT_d = 1.674 (mV/krad) measured on W12P4C05 for the HP 1.2 µm technology[1] The CMOS experiment pFET dose verifies dosimeter design and ground calibration methodology. The same equations rrre used to extract the pFET Z2 total dose on the Clementine spacecraft on 12 May 1995 shown in Figure 13. Where, Ts = 3.32 ("C) and, T = -2.41 ("C), VT = 863.9 (mV) measured on the Clementine pFET prior to launch, and the other variables are the same. CMOS radiation damage factors for n and p-channel transistors in HP 1.2 and 0.8 µm technologies are being utilized in radiation test structure designs for the Active Pixel image Sensors (AIN).

SRAM detector proton data from the 2] February 94 solar proton event have been compared to GOES-6 proton data. First, the Novice code was used to compute the proton environment as a function of energy inside the SRAM shields. Table 2 lists the external environment energy windows, Emin to Emax, in the 1 McV wide energy window measured in Figure 5. The internal environment fraction mean values, f_e, inside the shields arc also listed in table 2. Next the environment fractions were computed with the Novice code from a 2π-sr omnidirectional fluence of 1.96E9 (protons/cm-McV) at all energies outside the shields. The proton fluence was then reduced by the amount f_e inside the shields.

The SRAM spectrometers are sensitized to protons for 100s, every other 100 s period, for one hour, giving an on time fraction, f_{on}, of 0.S. The energy window width, ΔE (Figure 5), is

1 MeV. The instrument was designed with a 2π-sr field of view, Ω. The SRAM pixel sensitive area has an as drawn cross section, σ, of 42.12 μm^2. The spectrometer hourly fluence, F(E), in units of (protons/cm^2-sr-MeV-hr) is given by,

$$F(E) = \frac{18}{\sigma\ \Omega\ \Delta E\ f_e\ f_{on}} \ln\left(\frac{N_T}{N_T - N/18}\right) \tag{7}$$

Each pixel can only count one proton in each 100 s proton sensitive period and there are 18 sensitive periods each hour. There are 4096 pixels, N_T, on each SRAM chip and N is the measured number of counts per hour in each chip. The Clementine spectrometer data, F(E) from Eq. 7, for the Clementine SRAM Z2 and Z3 proton energy windows and the GOES-6 hourly fluencies for the proton energy windows P1 and P3 are plotted in Figure 14 for comparison,

The GOES-6 external environment proton energy windows, Emin and Emax, arc, P 1 = 0.6 to 4.2 MeV, P2 = 4.2 to 8.7 McV, P3 = 8.7 to 14 MeV, and P4 = 15 to 44 MeV. The Clementine and GOES-6 energy spectra for the total measured fluence on 21 Feb. 94 arc shown in Figure 15. The data point energies are taken at the center of the energy windows, (Emin + Emax)/2, listed in Table 2 for [he Clementine instrument and above for the GOES -6 instrument.

DOSIMETRY CONCLUSIONS

The primary objective of the RRELAX experiment was to monitor the radiation environment for the Clementine mission. Two conclusions have been presented vis-a-vis this objective. First, the ISAS CCD and CMOS experiment measurements were shown independently to compare favorably with the pFET dosimeter measured total dose. This demonstrates that [he results of the ground radiation tests can be used to accurately predict spacecraft sensor and electronic component radiation degradation. The test structure approach employed also allowed direct measurement of radiation effects in space and verified our predictive understanding, of the space environment's radiation effects on spacecraft sensors and electronic components. Secondly, the SRAM proton spectrometer successfully measured the proton fluence and energy spectrum, 'J-he data compared quite favorably with GOES-6 data for the same event. We therefore feel confident in stating that the dosimetry system, RADMON, has accurately tracked the proton fluence and energy and total dose for the Clementine Engineering experiments.

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[51 Sze, S. M.; Physics of Semiconductor Devices; John Wiley & Sons, Second Edition, 1981; Chapter 1, Eq. 19a; Chapter 2, Eq. 50.

TABLES

'J'able 1. pFET zero-dose ground voltages, V_g(mV), and aluminium equivalent shield thickness, d(mils), for each flight RADM(.)N on the JSAS RRELAX at T = 25 ("C) and on the Clementine Spacecraft RRELAX at T = -2.41 ("C),

RADMON Z#	Spacecraft V_g(mV)/d(mils)	ISAS V_g(mV)/d(mils)
Z2	129.9/01	621.8/07
Z3	074,8/31	335.4/37
Z5	274.8/61	592,2/67
Z4	381,()/91	494.0/97

"1'able 2 Clementine Spacecraft external environment energy windows and internal environment fractions, f_e, as a function of kovar shielding.

kovar shields (Z# - mils)	Emin (MeV)	Emax (MeV)	fe mean value (0.7-1,7 MeV)
Z2 - ()	2.16	3.16	0.261±0.031
Z3 - 10	11.81	12.81	0.072±0.009
Z5 - 2(J	16.96	17.96	0.047±0.007
Z4 -30	21.04	22.04	0.037±0.006

FIGURES

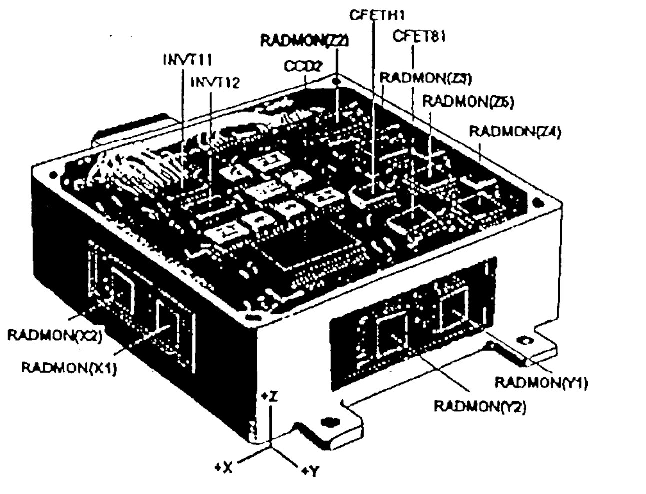

Figure 1. RRELAX experiment layout in 4" x 4" x].5" box

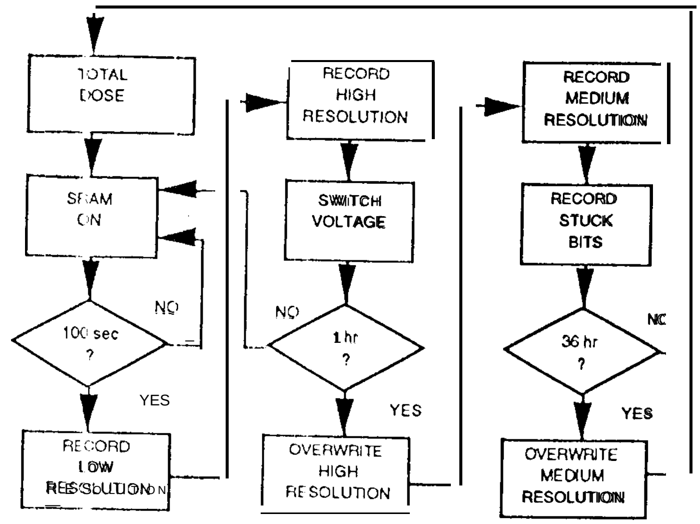

Figure 4. Software flow diagram showing SRAM data handling strategy.

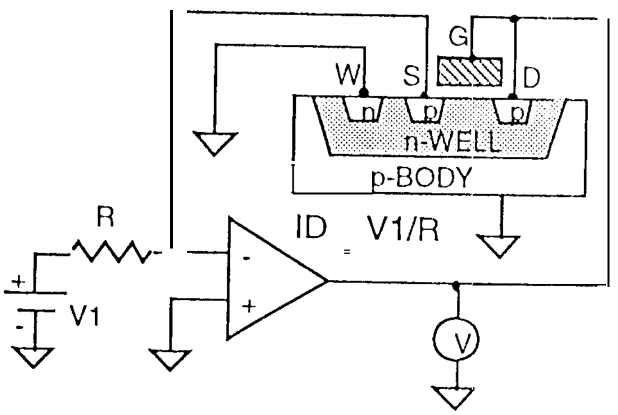

Figure 2. pFET on-SRAM-chip dosimeter and operating-mode circuit diagram.

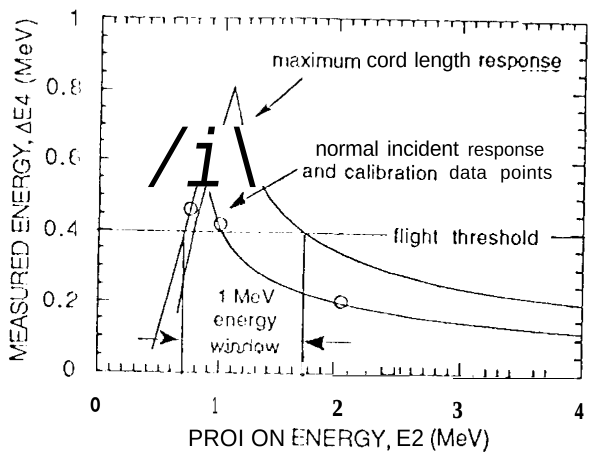

Figure 5. Clementine 1.2 μm technology proton calibration curves showing the flight energy threshold and the 1 MeV wide energy window.

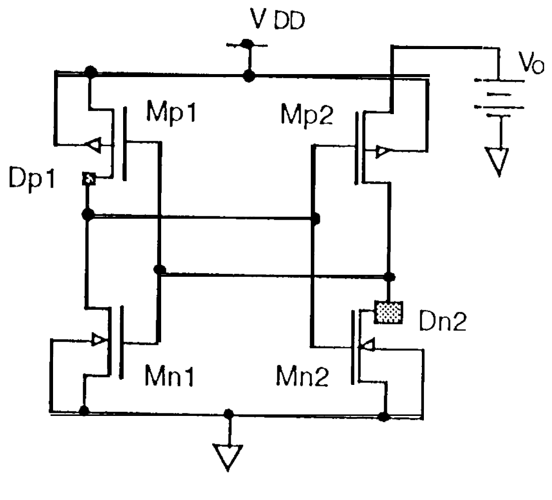

Figure 3. Schematic diagram of the SRAM cell showing the placement of V_O and the bloated n-drain, Dn2.

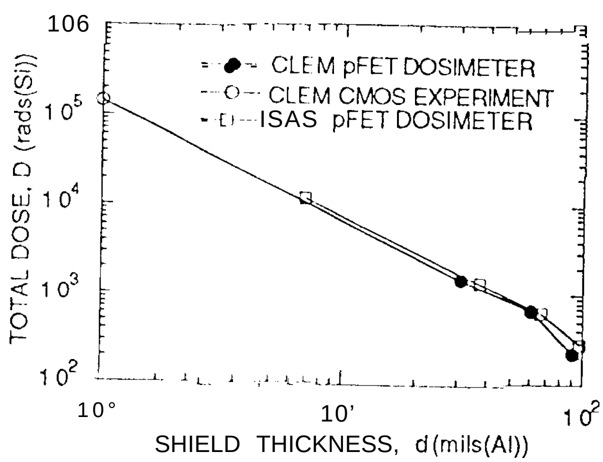

Figure 6, Total radiation dose on RADMON pFET Z2 as a function of aluminium equivalent shield depth for the Clementine spacecraft on 12 May 95 and (he IS AS on 20 Apr. 94.

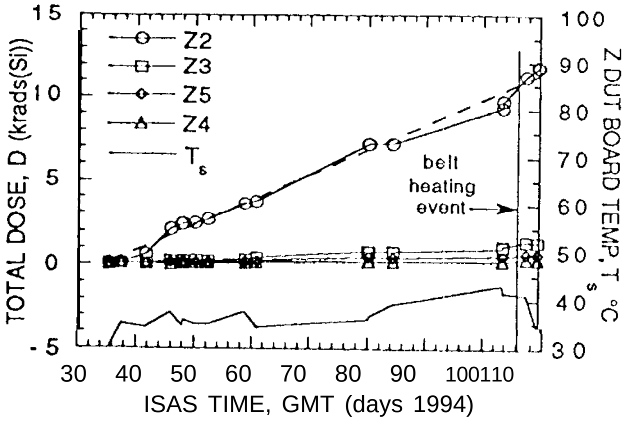

Figure 7. Mission dose profile for the ISAS RADMON pFETs in a 2.13 day lunar transfer orbit and the associated temperature. variation.

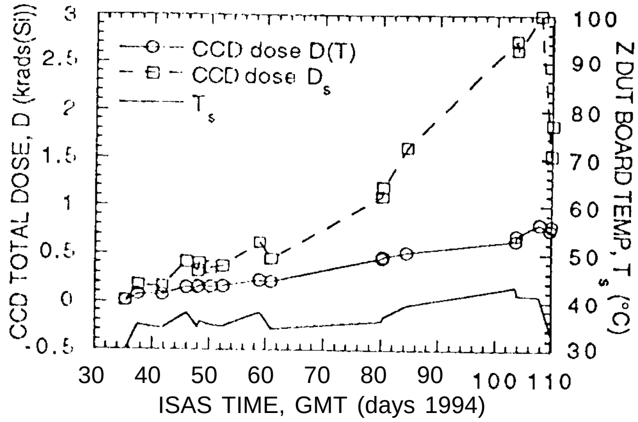

Figure 10. CCD temperature corrected, D(T), and uncorrected D_s dose data as a function of temperature.

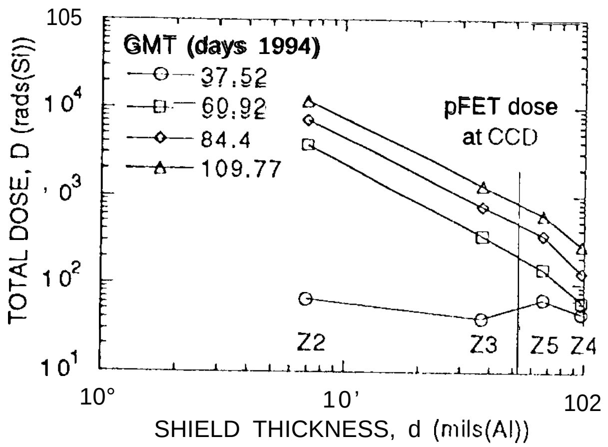

Figure 8. ISAS dose-depth curves showing pFET dose at CCD2.

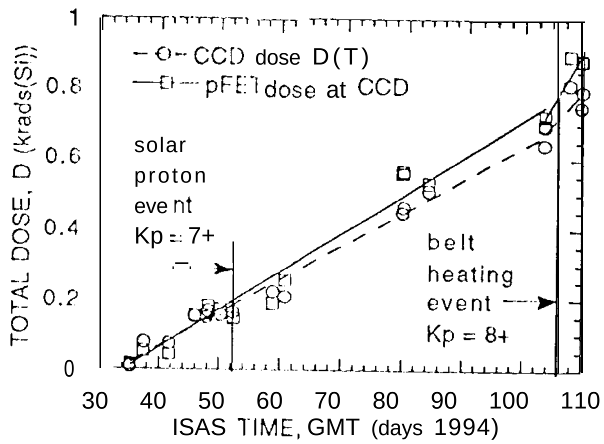

Figure 11. CCD dose D(T) and pFET dose at the CCD showing increased dose rate after day 106.

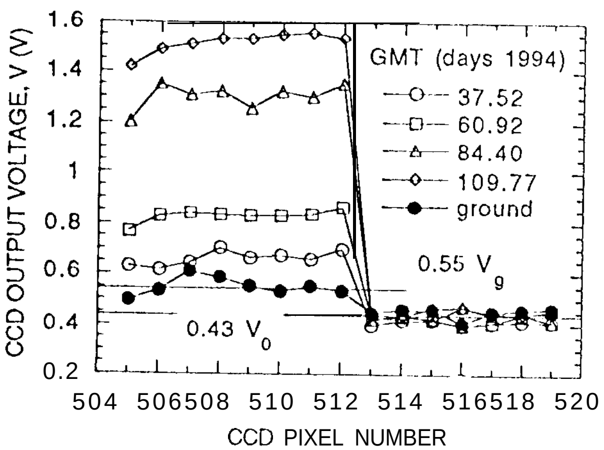

Figure 9. A sample of the RRELAX ISAS CCD2 data showing the prelaunch, zero dose, pixel voltage mean, V_g, and the extended pixel voltage mean, for ground and space data, V_0.

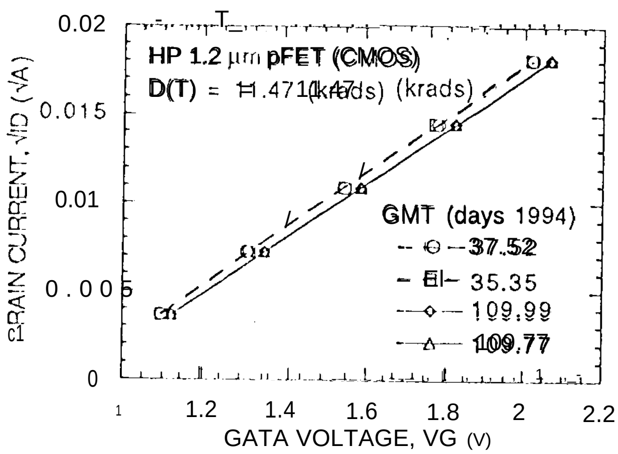

Figure 12. ISAS CMOS HP 1.2 µm pFET gate voltage shift on day 109.99, 20 Apr. 1994.

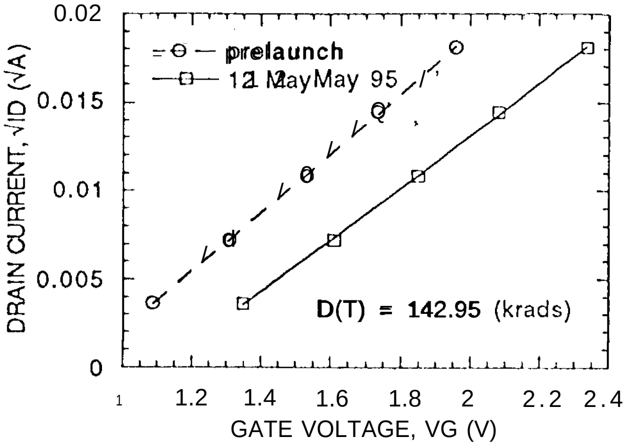

Figure 13. Clementine CMOS 11P 1.2 μm pFET Z2 gate voltage shift on 12 May 1995.

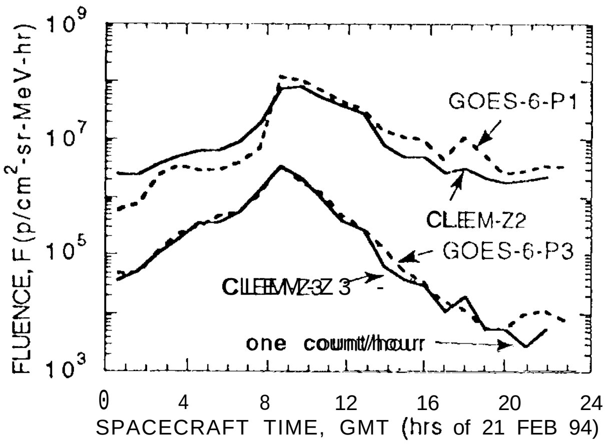

Figure 14. Comparison of Clementine data to GOES-6 data during the 21 Feb. 94 solar proton event. The proton spectrometer sensitivity of one count per hour is shown.

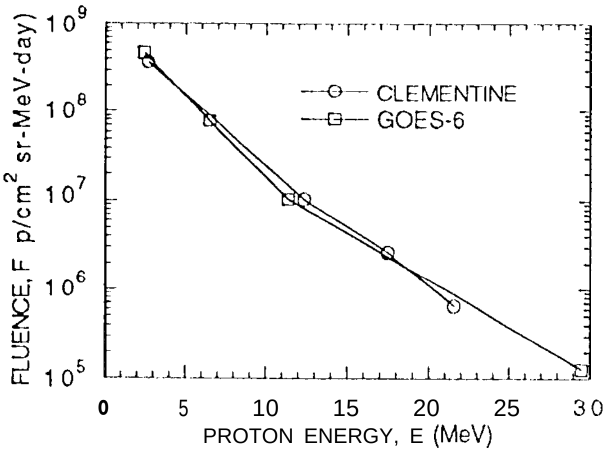

Figure 15. Clementine spacecraft and GOES-6 external environment proton energy spectra cm 21 Feb. 94.